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PROGRESS REPORT 235-6

CAVITATION DAMAGE IN LIQUID METALS

Report of Progress
for the Period
2 July - 2 October 1963

By
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Prepared for
National Aeronautics and Space Administration
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CAVITATION DAMAGE IN LIQUID METALS

Report of Progress
for the Period

2 July - 2 October 1963

SUMMARY:

During the current period, a contract was let to S. Blickman, Inc. in Weehauken, N. J. for the fabrication and installation of the vacuum dry box for cavitation damage testing of refractory metals at high temperature. Detailed shop drawings have been completed and fabrication is underway. All associated auxiliary systems such as cooling, cover gas, sodium storage and charging and electrical instrumentation have been designed and are in process of fabrication or procurement. It is planned to discuss the test facility in detail in the next report at which time installation and check-out should be completed.

Further experiments were performed to determine the effect of specimen diameter on damage rate in the magnetostriction device. The results indicate that the damage rate varies as the square of the diameter within the limits tested; however the intensity of damage is independent of diameter. These data permit rates of damage to be compared for flat specimens of any diameter from 3/8" to 7/8" in size.

A series of experiments were performed on commercially pure iron (Ferrovac-E) and Titanium (100-A) to determine the effects of time, amplitude and temperature on the rate of cavitation

damage in liquid sodium. It is shown that the damage rate for iron at 400°F and 700°F and Ti at 400°F varies with test duration following the characteristic pattern of four zones of damage discussed in the earlier Progress Report 235-4.

Amplitude studies made on pure iron at 400°F show that in the steady state zone the amplitude varies as a function of the fourth power but at higher temperatures such as 700°F, the damage varied considerably less than the fourth power. The data are inconclusive, however, since at the higher temperature the threaded stud of the specimen sheared off during each test.

The effect of temperature on the damage rate was determined for titanium at a constant amplitude. The rate of damage increased with increasing temperature until a maximum of 800°F and then decreased with increasing temperature to 1000°F. Considerable scatter was observed in these experiments. A detailed discussion of these data and other data are included in the body of this report.

Some preliminary fatigue tests were conducted with a 1020 steel specimen in liquid sodium at 300°F. The results show that a typical S-N curve can be obtained by means of a comparatively new high frequency vibratory technique. The testing method is discussed in detail in the body of this report.

EFFECT OF SPECIMEN DIAMETER ON CAVITATION DAMAGE RATE

(a) Procedure:

A series of flat Aluminum 1100-F specimens were prepared varying in diameter from 1/4" to 1" in increments of 1/8". All buttons were cavitated in the magnetostriction device in distilled water at 80°F until the steady zone was reached. The amplitude was held constant at 1 x 10^{-3} inches (25.4 u). The frequency was maintained approximately constant at 16 kcs. The variation in specimen weight necessitated the adjustment of the horn rod length to compensate for minor shifts in the resonant frequency of the system.

(b) Observations:

The rate of weight loss in the steady zone was computed as a function of specimen diameter and was found to vary as the square of the diameter. This is shown on Figure 1 where the rate of weight loss, plotted against $(\text{diameter})^2$ results in a linear relationship. The appearance of the surface of specimens at the conclusion of the test are illustrated in Figure 2. All of the specimens were roughened uniformly with deep craters characteristic of the steady zone. Further spot checks were made with several of the specimens cavitated at different amplitudes. The rate of weight loss for a specimen of given diameter was found to vary as the square of the amplitude as would be expected from previous work (4). It should be noted that each specimen, regardless of diameter, had a peripheral rim of no damage of a constant width of approximately 1/16". This phenomenon overshadowed the remaining cavitated area on the 1/4" diameter specimen so as to make weight loss correlation impractical for this size specimen. Also, difficulty was experienced in achieving stability with the 1" diameter specimen. The large overhang caused excessive strain at the threaded stud of the specimen resulting in cracks.

(c) Discussion:

The rate of weight loss due to cavitation damage in the steady state zone at a given amplitude and frequency is directly proportional to the square of the diameter of the specimen within the limits of 3/8 to 7/8 inch diameter for flat specimens. The rate of volume loss is divided by the area of the specimen ($\pi d^2/4$) and this value was found to be independent of the specimen diameter as shown in Figure 3. This result leads to an interesting conclusion that the intensity of cavitation damage is independent of the specimen diameter within the range tested, in the case of magnetostriction apparatus, in the steady state zone (the intensity being as defined in Reference 10).

It is believed that this result might be useful in correlating damage rates from specimens other than the commonly used 5/8 inch diameter ones, since the bar stock material of this particular size may not be available in some cases.

Experimental Procedure for Sodium Tests

All liquid sodium tests were performed in the inert atmosphere magnetostriction apparatus described in previous reports. In this series of experiments however, a cold trap was installed in the bottom of the retort which also served as a drain line. The arrangement is shown in Figure 4. The cold trap was maintained at 250°F or less throughout the experiments. Solid sodium bricks (Dupont-regular grade) were melted down in the retort and were skimmed of any surface oxides by means of a screen mesh ladle. The oxide contamination was kept to a minimum by continuous cold trapping. No sodium sampling was made. All temeratures were maintained constant to ±20°F. All weight losses were measured to the nearest 0.1 mg after cleaning the specimen in methyl alcohol and drying by heating in an alcohol flame. All weight losses determined as a function of amplitude or temperature were made after the specimen reached the steady zone state.

EFFECT OF TIME ON CAVITATION DAMAGE RATE

(a) Observations:

Cavitation damage rates as a function of time were determined for pure iron (Crucible, Ferrovac E) at temperatures of 400 and 700°F and for Titanium (TMCA, 100A) at 400°F. The oscillation double amplitude for the iron specimen was held at 1.5 mils (38 μ) and for Titanium 1.8 mils (45.7 μ) with a resonant frequency of 14.9 and 15.5 kcs respectively. Weight losses were taken periodically for each specimen and the rate of weight loss during each time interval is plotted over the test durations as shown in Figures 5 and 6. It is clearly discernible that the curves follow the characteristic damage pattern observed by aluminum and other metals in tap water as shown in Figure 7, and as described in the previous report (1).

The similar appearance of the iron specimen in sodium at 700°F in the incubation, accumulation, attentuation and steady state zones to that of aluminum in tap water are shown by comparing Figures 8 and 9 which show progressive damage plotted in the corresponding curves 5 and 7 respectively. An attempt was made to get the damage rate curve for iron at higher temperatures. However, during the tests the button kept shearing off at the threads and therefore this phase of the experiment was suspended temporarily.

As can be seen from Figures 5 and 7, the rate of damage of iron in liquid sodium at 700°F in all the zones is in the same order of magnitude as that of aluminum in tap water. However, for a more accurate comparison, the differences in amplitude must be taken into consideration. It is interesting to note that there is practically no existence of an incubation zone for either iron in liquid sodium or aluminum in tap water at the particular amplitudes selected.

Figure 5 shows clearly the interaction of time on cavitation damage rates of iron in liquid sodium at two temperatures. It is precisely because of this anomalous behavior in the various zones of damage that meaningful comparisons are only possible at present, in the steady zone.

The damage rate of Ti-100A as plotted in Figure 6 shows practically no incubation time, with accumulation rates beginning almost instantaneously. The maximum rate of weight loss for titanium compared to iron under nearly constant conditions of amplitude, frequency and temperature is 0.67 mg/min to 2.7 mg/min respectively. This maximum is reached after a much longer accumulation time for titanium and the weight loss in the steady zone after 700 minutes of test duration is 0.26 mg/min , much lower than that observed for iron (0.68 mg/min) under similar test conditions.

(b) Discussion:

The materials for this series of experiments, pure iron and titanium, were selected on the basis of their good static corrosion resistance to liquid sodium as reported in the literature (2)(3). The behavior of these materials in liquid sodium (in the absense of substantial corrosion effects) exhibiting characteristic cavitation damage zones as observed for a great variety of materials in water, should allow similar empirical mathematical analysis and treatment for relating the major parameters affecting the rate of cavitation damage. Further confirmatory data are needed for several other materials before this approach can be followed. It is evident from the start however that the temperature affect is one of the more critical parameters affecting cavitation damage rate. It is reasonable that this is so, inasmuch as temperature will affect bubble formation and collapse and energy, transfer and absorption. Temperature will also affect the chemical reactivity of the sodium and its contaminants, with materials under consideration. Lastly, temperature will affect the physical and mechanical properties of the material, especially its strain energy.

EFFECT OF AMPLITUDE ON CAVITATION DAMAGE RATE

(a) Observations:

Pure iron, after reaching the steady zone, was tested in the magnetostriction device at various amplitudes with frequency (14.9 kcs) and temperature held constant. Weight losses were taken on the same specimen at a selected amplitude. Several runs were made at 400°F and 700°F. Considerable scatter was observed for the 700°F run. The average values of rate of weight loss as a function of amplitude are plotted in Figure 10. As can be seen in this figure, the damage rate varies as the fourth power of the amplitude for the 400°F sodium but appears to have a marked change of slope at the higher temperature. Unfortunately, because of specimen breakage during the experiment it was not possible to define the slope of the 700°F curve accurately.

(b) Discussion:

It has been determined experimentally for several materials that the rate of weight loss varies as the square of the amplitude in the steady zone, when cavitating a specimen in water using a magnetostriction device (4). This relationship is shown in Figure 11.

It appears that in sodium the rate of weight loss varies to some power of amplitude, not necessarily the second power. Temperature seems to interact with amplitude in determining the rate of cavitation damage. Until further experiments are performed no conclusion can be drawn on the effect of amplitude on the damage rate in liquid sodium.

EFFECT OF TEMPERATURE ON CAVITATION DAMAGE RATE

(a) Observations:

Since the pure iron specimens consistently failed (shearing of the threaded stud) at temperatures of 700°F, it was only feasible to determine the cavitation damage rate of titanium over a considerable temperature range (1000°F) at a constant frequency (15.5 kcs) and amplitude (45.7 μ). The specimen after reaching the steady zone was run for periods of one to two hours at a constant temperature. Several runs were made at each temperature with considerable scatter observed. However, after several tries the curve in Figure 12 was obtained. It is indicated from the curve that the rate of weight loss increases with increasing temperature until a maximum at 800°F and then decreases markedly beyond this temperature.

(b) Discussion:

The behavior of a given material in a cavitating environment as a function of temperature is difficult to predict or explain on the basis of one curve. It is obvious that many parameters are affected by temperature and therefore these will have to be singled out and studied before a rational analysis can be attempted. In the case of titanium, it is believed that the stress rupture characteristics and oxide contamination, as functions of temperature, play significant roles in the damage process.

It is quite clear from the above few experiments that considerably more data are needed before some generalizations can be made. Work will continue with titanium and iron, in addition to pure nickel, 316 ss, Inconel 600 for the next series of tests.

Preliminary Fatigue Studies

In the magnetostriction cavitation damage studies there appears a period of time during exposure in which no damage occurs. This effect has been termed "incubation time" and it has been suggested by Leith(5) that this phenomenon is related to corrosion fatigue. Of direct interest in this program is how the fatigue properties of a material affects the cavitation damage process. Practically no data are available in the literature on fatigue in liquid sodium at high temperature (6). For the past several months investigations have been made of an accelerated fatigue testing method conducted at frequencies corresponding to those used in the magnetostriction device (7)(8). The method appears ideally suited since the strain rates are of the order of those encountered in the cavitation damage process under study. In addition, the rapidity of the test permits extensive studies to be made. At 15 kcs cyclical stressing, the limiting number of cycles, set at 10^8, can be achieved in two hours.

The specimen selected for the fatigue studies is shown in Figure 13. The basis of design of this type of fatigue specimen is as follows (9). The solution of the one dimensional wave equation for the wave travelling in a stepped cylindrical rod with diameter d_1, over a length ℓ_1 and diameter d_2 over a length ℓ_2 is given by

$$\tan k\ell_1 + p \tan k\ell_2 = 0$$

where

$$K = \frac{2\pi f}{c}, \quad p = \frac{d_1^2}{d_2^2} \qquad [1]$$

f = frequency

c = velocity of sound in the material.

The solution of Equation [1] is obtained graphically as shown in Figure 14. Since an abrupt change in the diameters would produce stress concentrations, a smooth tapered transition is provided. The altered length ℓ_2 due to this transition is experimentally determined by adjusting the length.

The specimen was calibrated by measuring the displacement amplitude along the specimen by means of a microscope and by plotting the amplitude as a function of the longitudinal distance as shown in Figure 15. The slope of this curve gives the strain along the longitudinal axis of the specimen and the maximum strain is directly proportional to the voltage developed in a pick up coil located above the fatigue specimen as shown in Figure 16. Figure 17 shows the relationship between the measured value of the strain, and the calculated value (the calculation being made on the assumption that a pure sine wave travels along a uniform rod). The measured value is about 0.87 times the calculated value because of the distortion of the wave due to the taper. There are a few limitations to this calibration:

1. Reproducibility of specimen geometry and control of surface roughness while machining.

2. Effect of high temperature environment in the case of sodium experiments. Attempts are being made to overcome these limitations.

Using the techniques described above a series of 1020 mild steel specimens was vibrated in liquid sodium at 300°F. Each point (■) plotted in Figure 18 represents the fatigue failure of a single specimen at a given stress after the elapse of the corresponding number of cycles of alternate stressing. Data for mild steel in distilled water using the same method is included for additional information. Figure 19 shows the failure of a typical fatigue specimen in sodium.

Discussion:

These preliminary tests show that the method is suitable for obtaining S-N curves at high frequency. As more data became available and as the technique is refined, it is expected that a rational analysis of the role of fatigue in the cavitation damage process can be obtained. Important questions of the effect of frequency, temperature and corrosion on fatigue behavior will be studied.

Refractory Metals Drybox Facility

The new refractory metals drybox is presently being fabricated by S. Blickman, Inc. The facility will include means for evacuation of the drybox to 2.5 microns and backfill with argon up to 5 psig. The drybox will have a false bottom for water cooling and contain an elevating mechanism for calibration and operation of the magnetostriction apparatus. A sodium transfer and purification loop will be incorporated into the system for ease of handling. Instrumentation for monitoring moisture and O_2 contamination of the cover gas will be provided. The drybox is scheduled for delivery in January 1964. A complete description of the facility and its calibration will be included in the next progress report.

PLANS FOR NEXT PERIOD

1. Determine effect of surface roughness on cavitation damage rate.

2. Continue experiments with pure iron, titanium, nickel, Inconel and 316 ss on the effects of time, amplitude, temperature and frequency on the cavitation damage process.

3. Continue fatigue tests on the above materials.

4. Install and calibrate new refractory metals drybox facility.

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9. Tanaka, S., "Ultrasonic Fatigue Testing," Rep. Inst. High Sp. Mech., Japan, Vol. 13 (1961/1962), No. 129.

10. Thiruvengadam, A., "A Comparative Evaluation of Cavitation Damage Test-Devices," Technical Report 233-2, HYDRONAUTICS, Incorporated, November 1963.

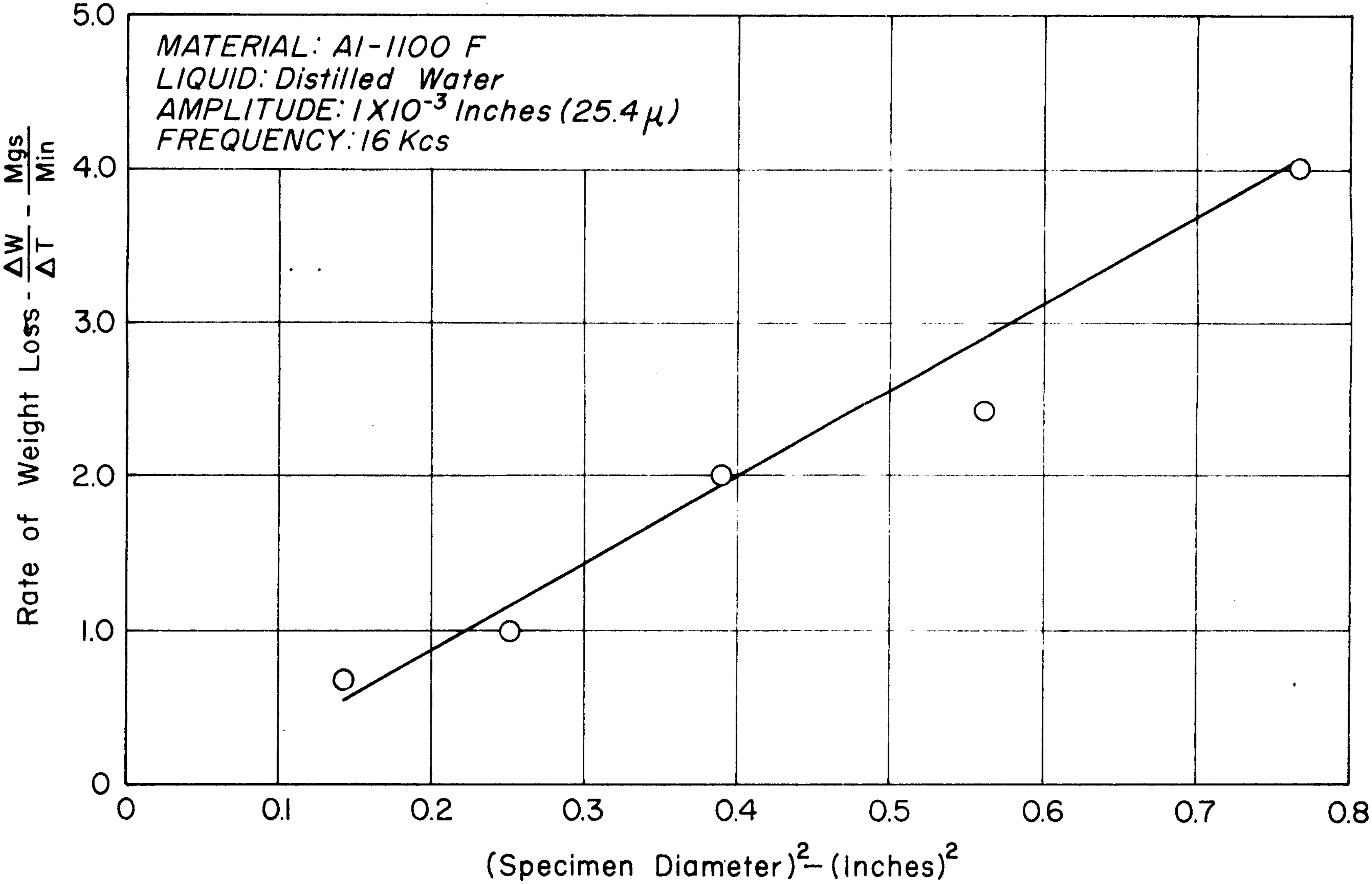
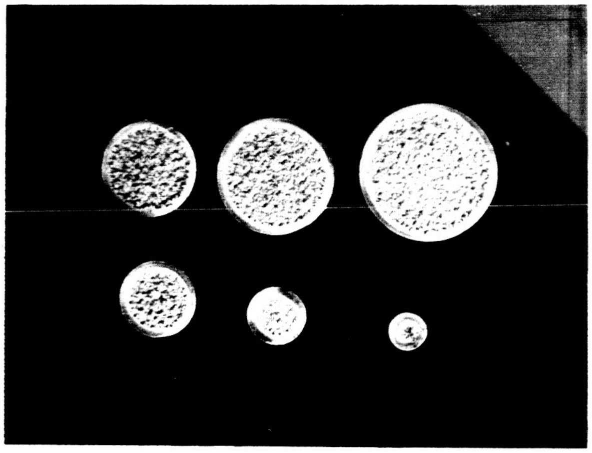


Figure 1-Rate of Weight Loss Vs. Specimen Diameter^2



MATERIAL: Al-1100-F
DIAMETER: $\frac{1}{4}$" - $\frac{7}{8}$"
LIQUID: Distilled Water, 80°F

STEADY ZONE CAVITATION DAMAGE PATTERN FOR VARIOUS DIAMETERS

Figure 2

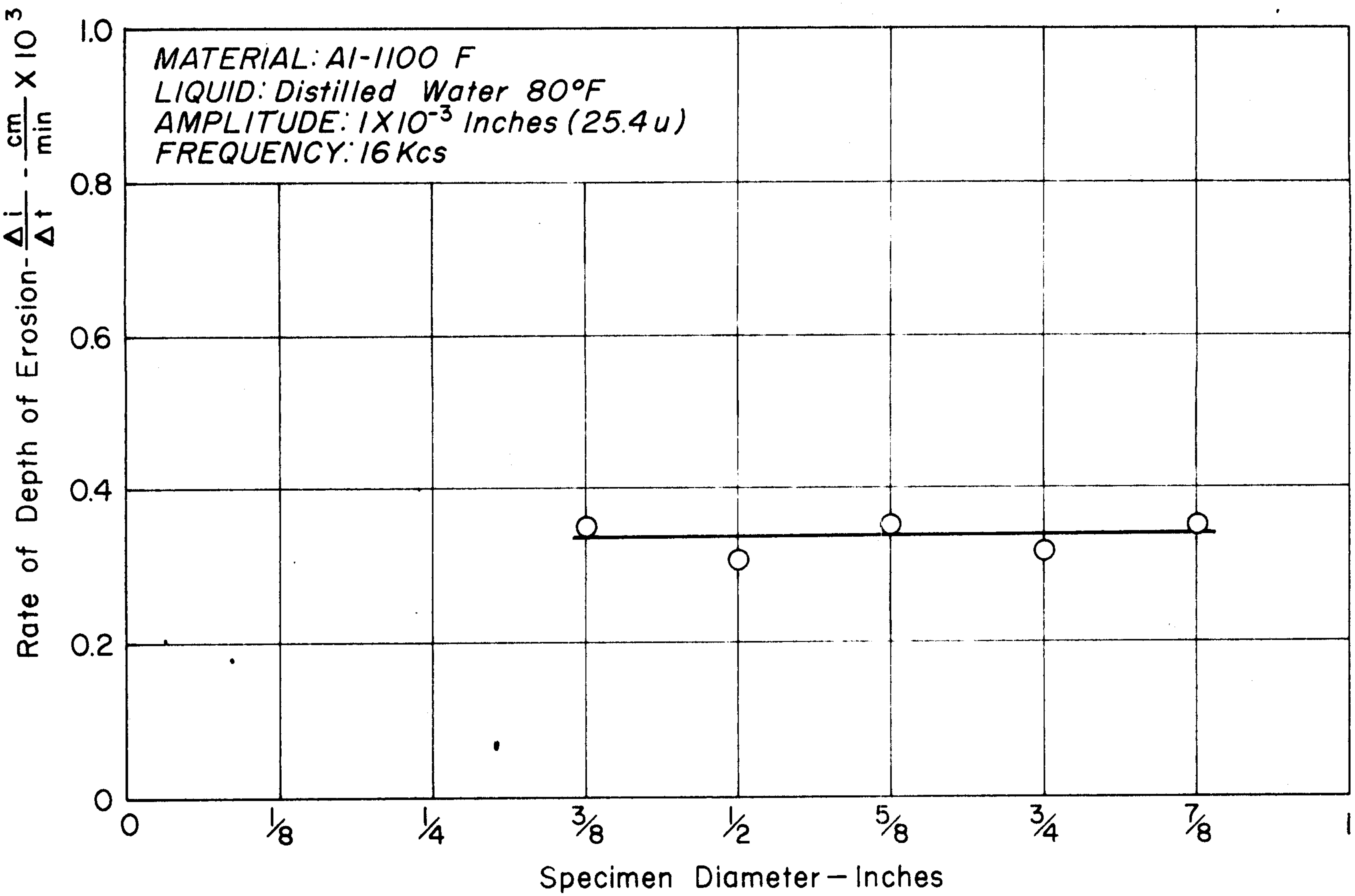
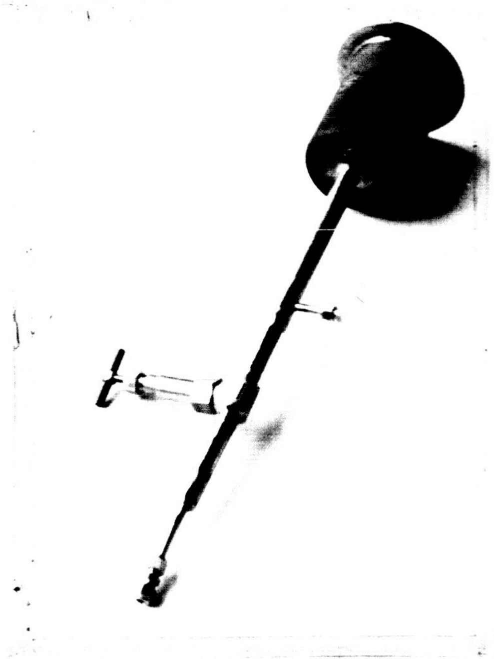


Figure 3-Rate of Average Depth of Erosion as a Function of Specimen Diam



COLD TRAP ASSEMBLY

Figure 4

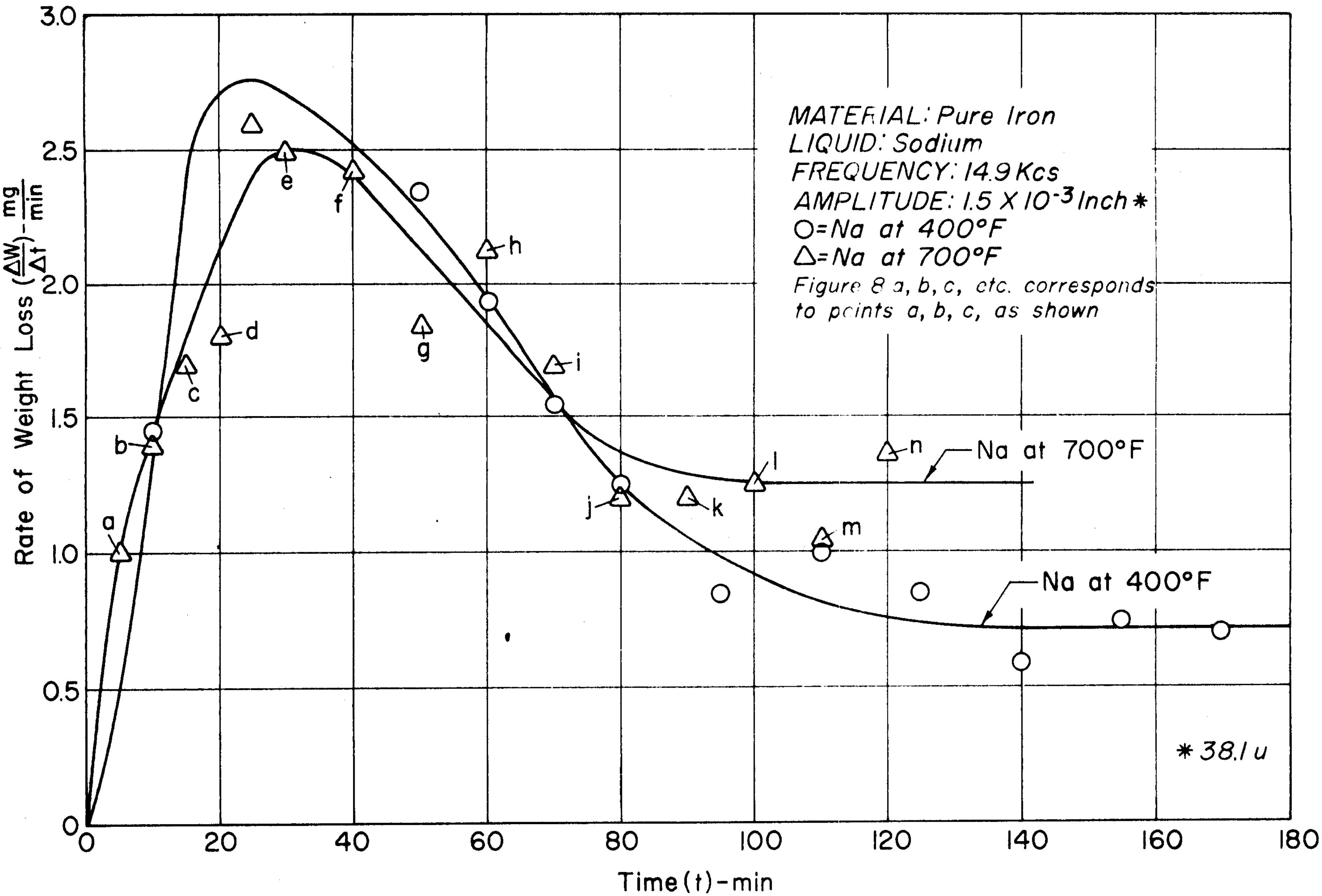


Figure 5-Cavitation Damage Rate as a Function of Time

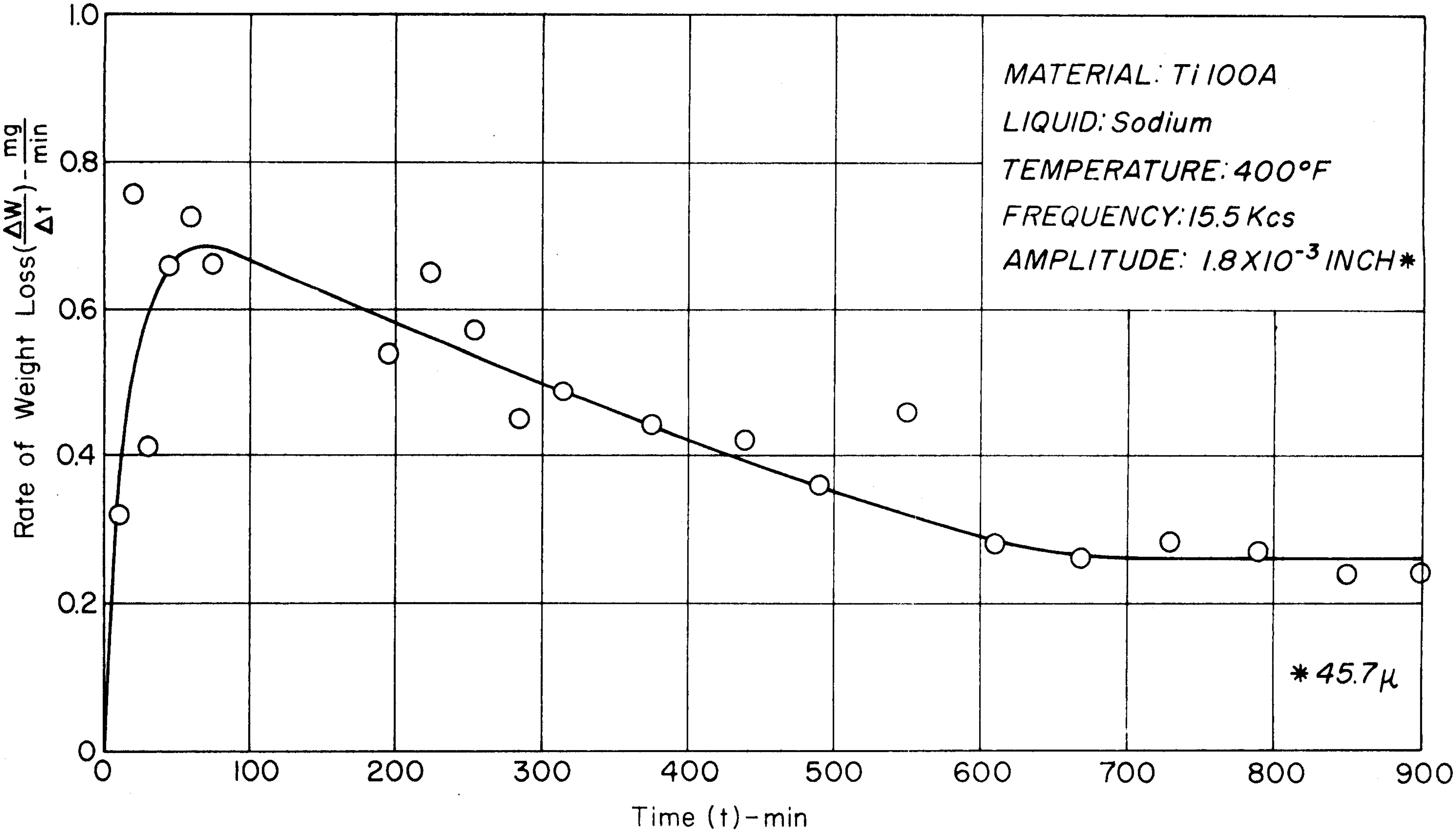


Figure 6–Cavitation Damage Rate as a Function of Time

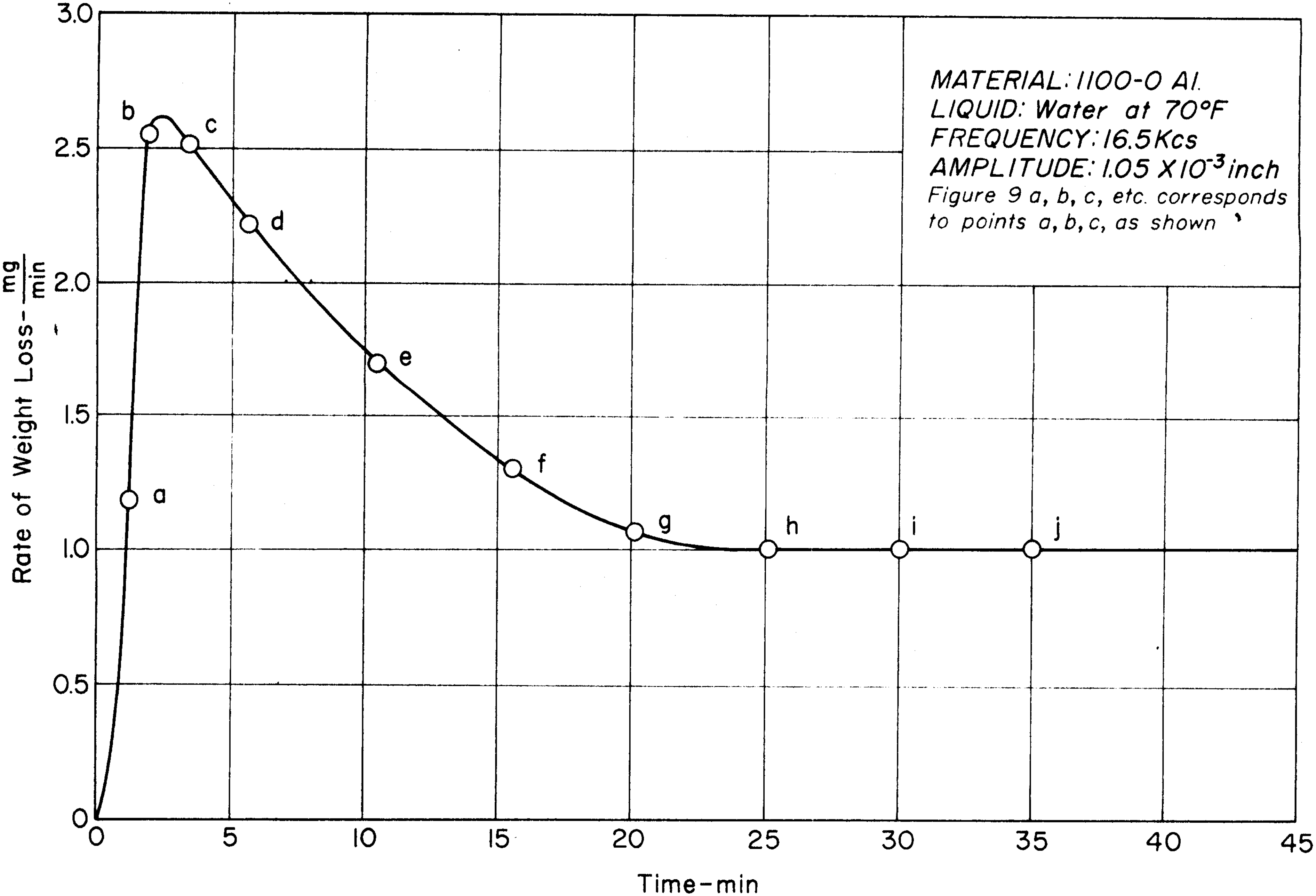


Figure 7-Rate of Weight Loss as a Function of Time

PROGRESSIVE CHANGES IN THE APPEARANCE OF THE DAMAGED SURFACE

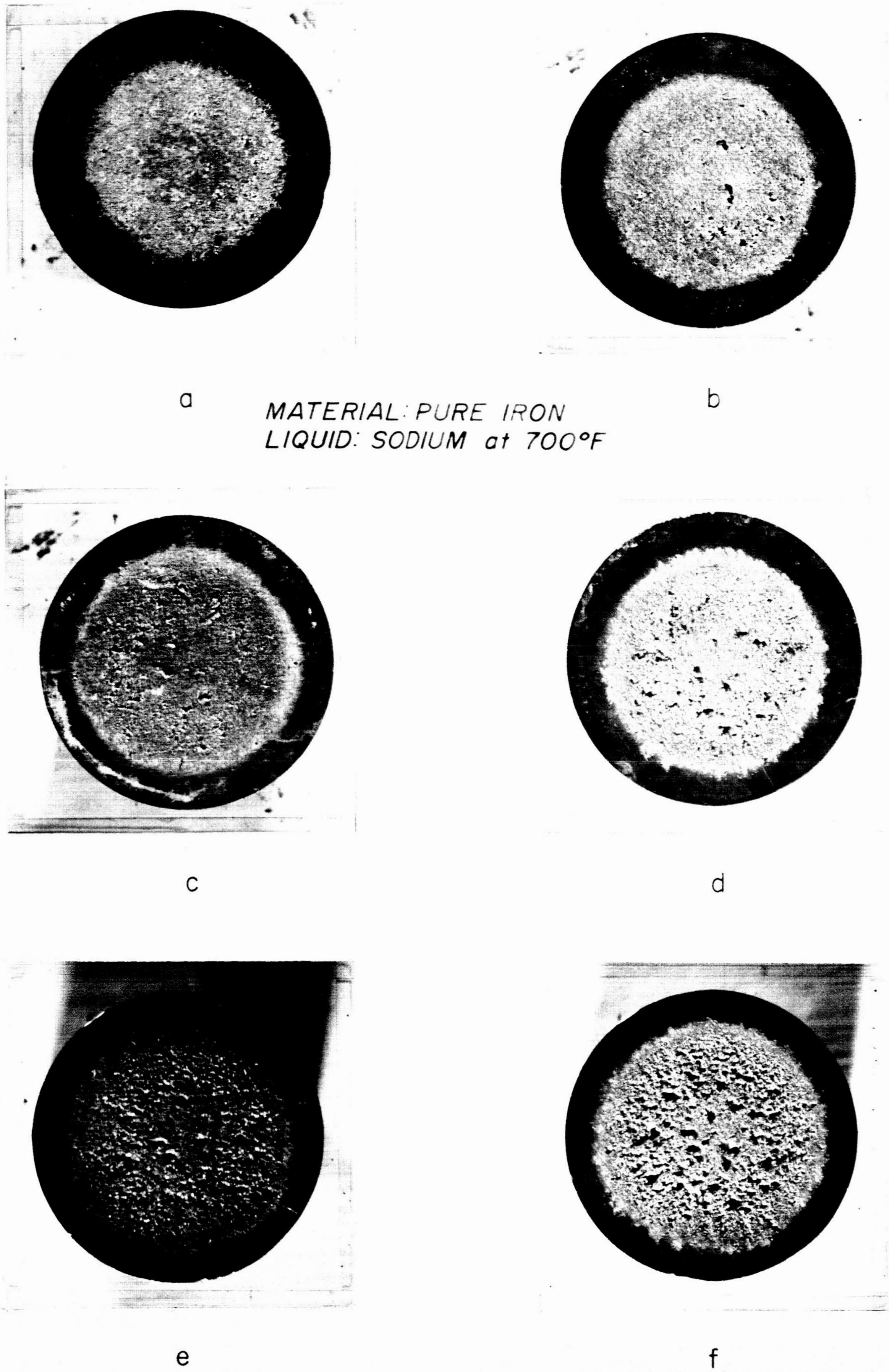
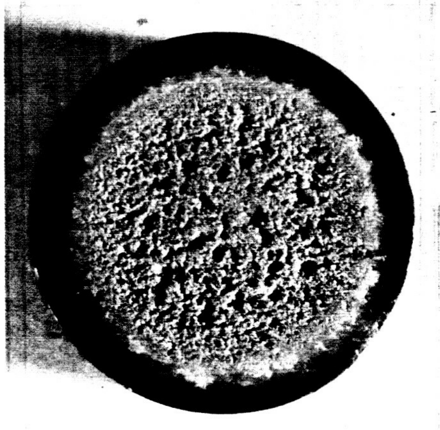


Figure 8

PROGRESSIVE CHANGES IN THE APPEARANCE OF THE DAMAGED SURFACE



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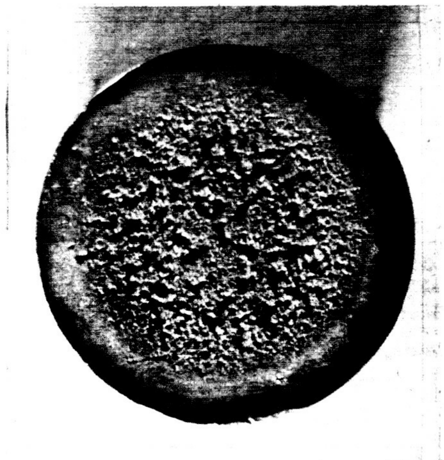

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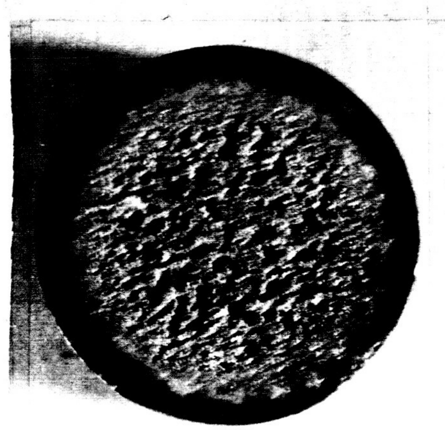
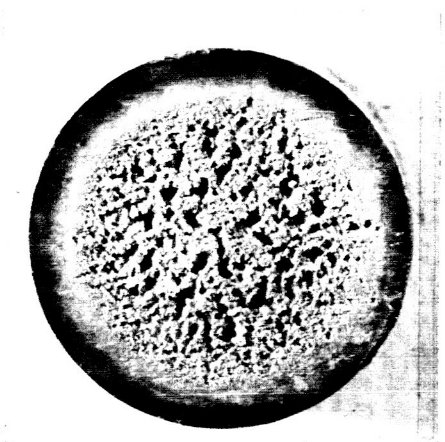


i

MATERIAL: PURE IRON LIQUID: SODIUM at 700°F



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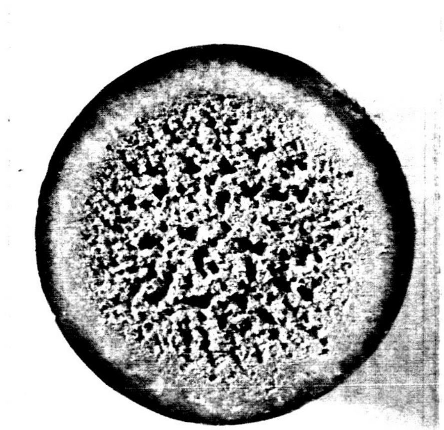

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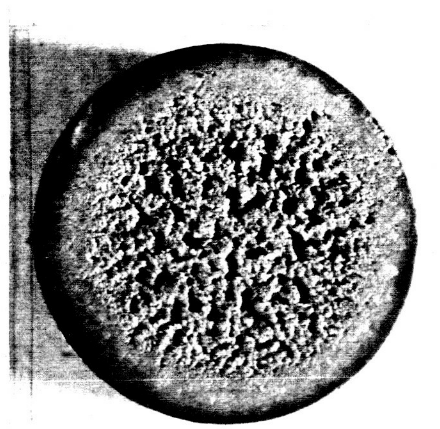

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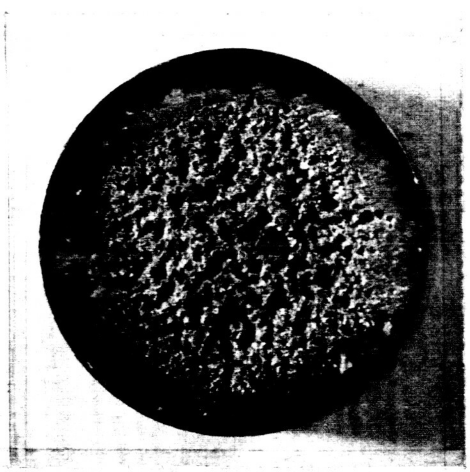

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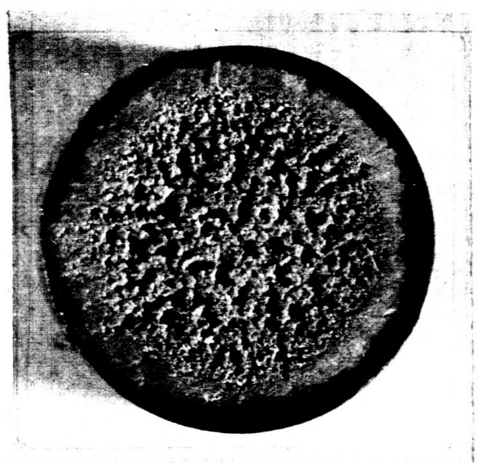

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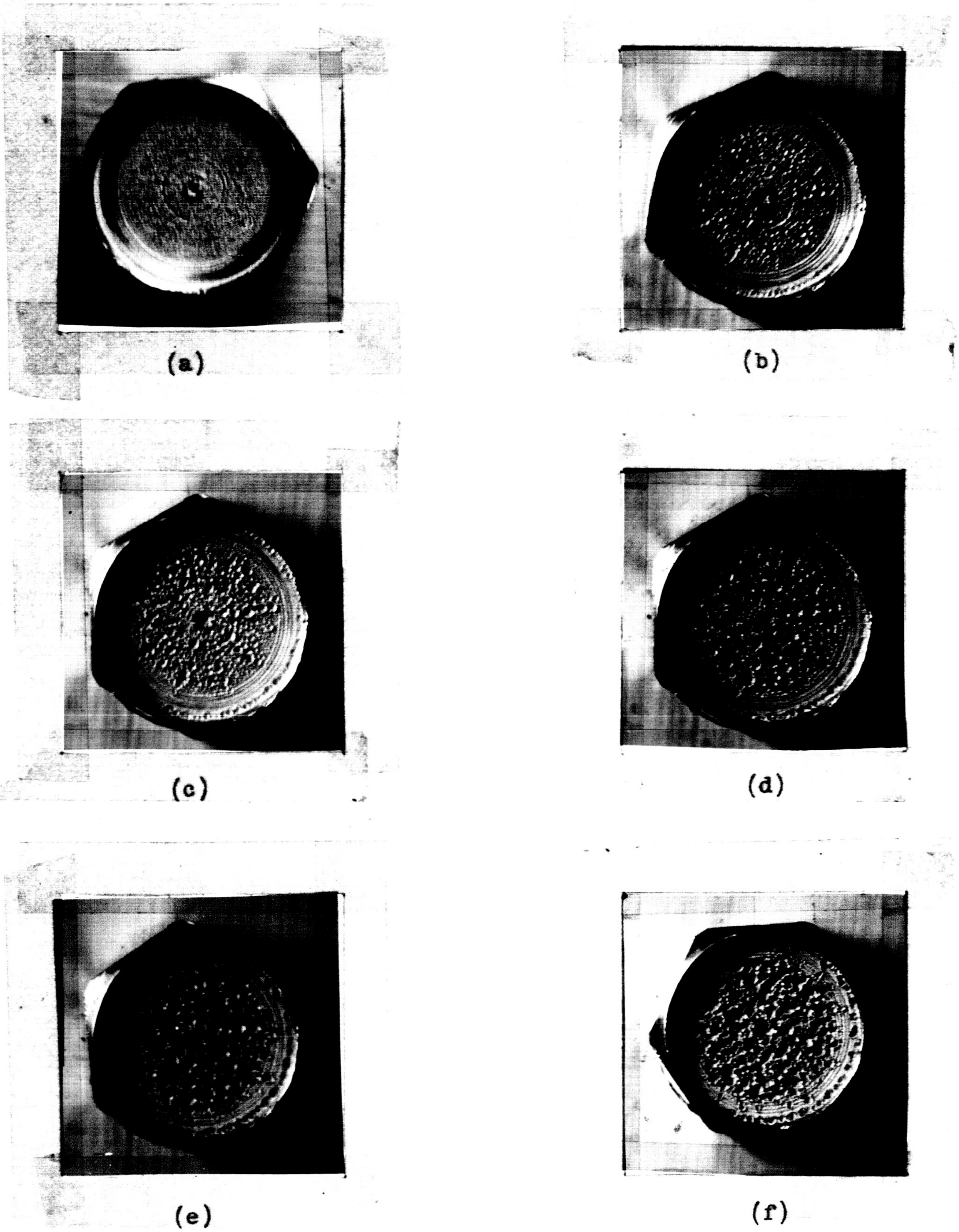
Figure 8

PROGRESSIVE CHANGES IN THE APPEARANCE

OF THE DAMAGED SURFACE



(a) (b)

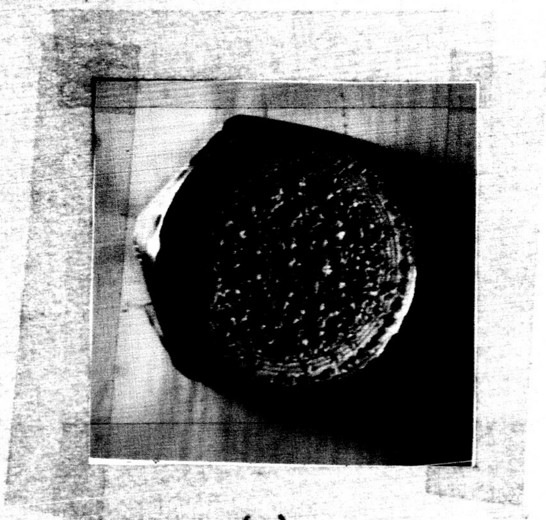
(c) (d)

(e) (f)

FIGURE 9

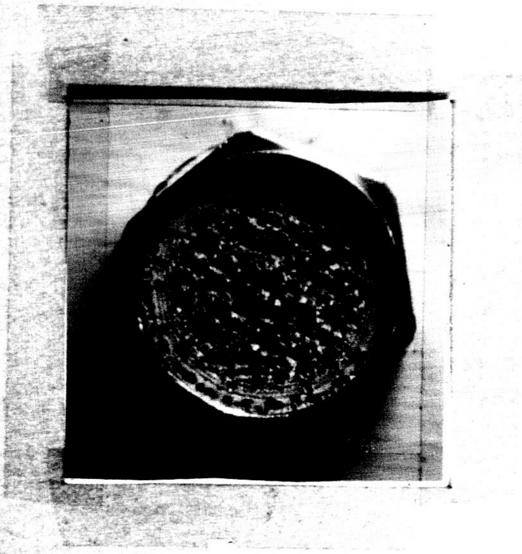
Al 1100-O
Tap Water

PROGRESSIVE CHANGES IN THE APPEARANCE
OF THE DAMAGED SURFACE

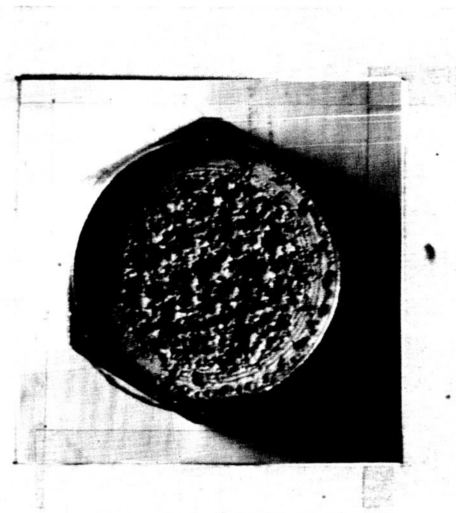


(g)

(h)



(i)



(j)

FIGURE 9

MATERIAL: Al 1100-0
LIQUID: Tap Water

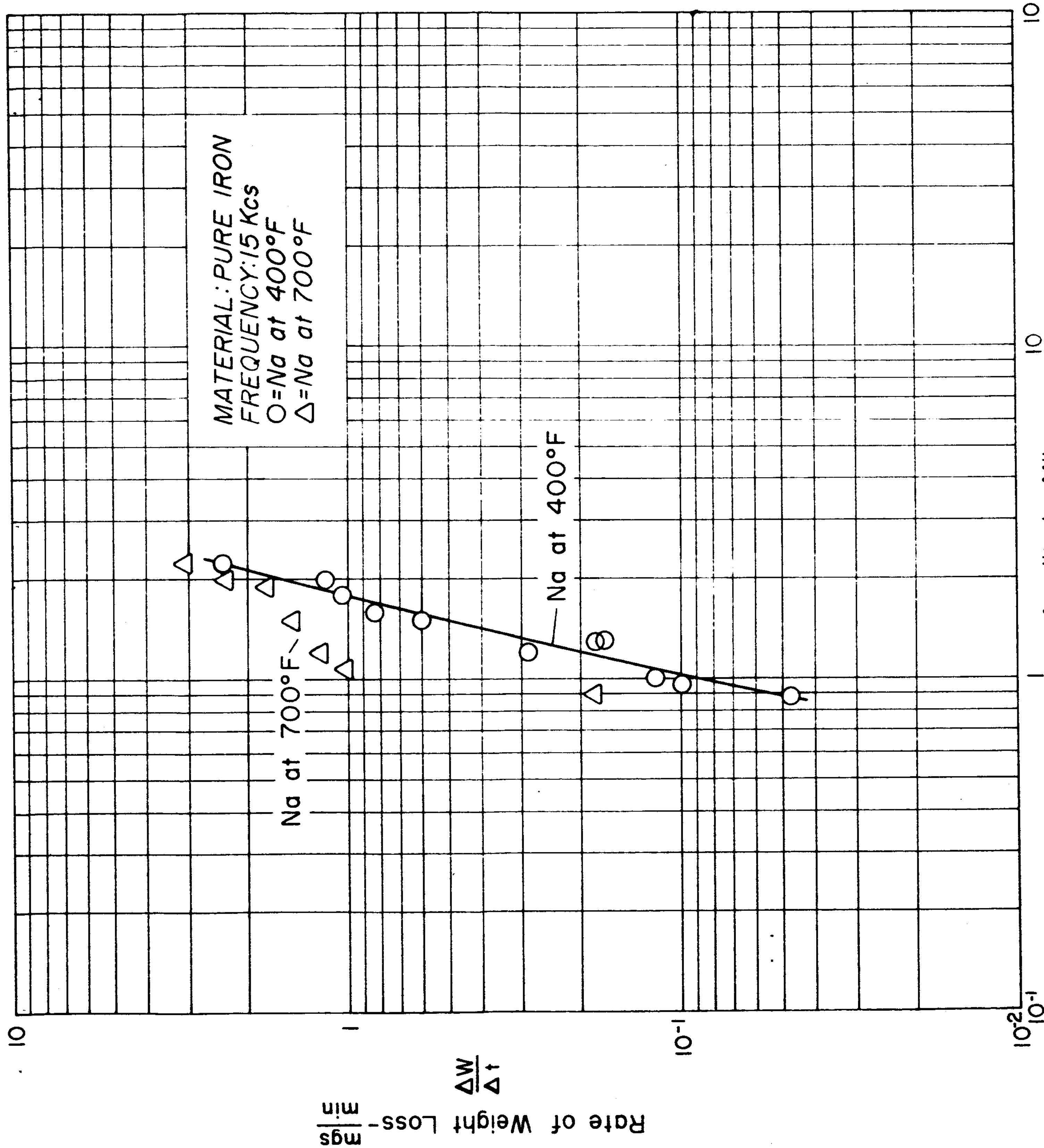


Figure 10-Effect of Amplitude on Damage Rate

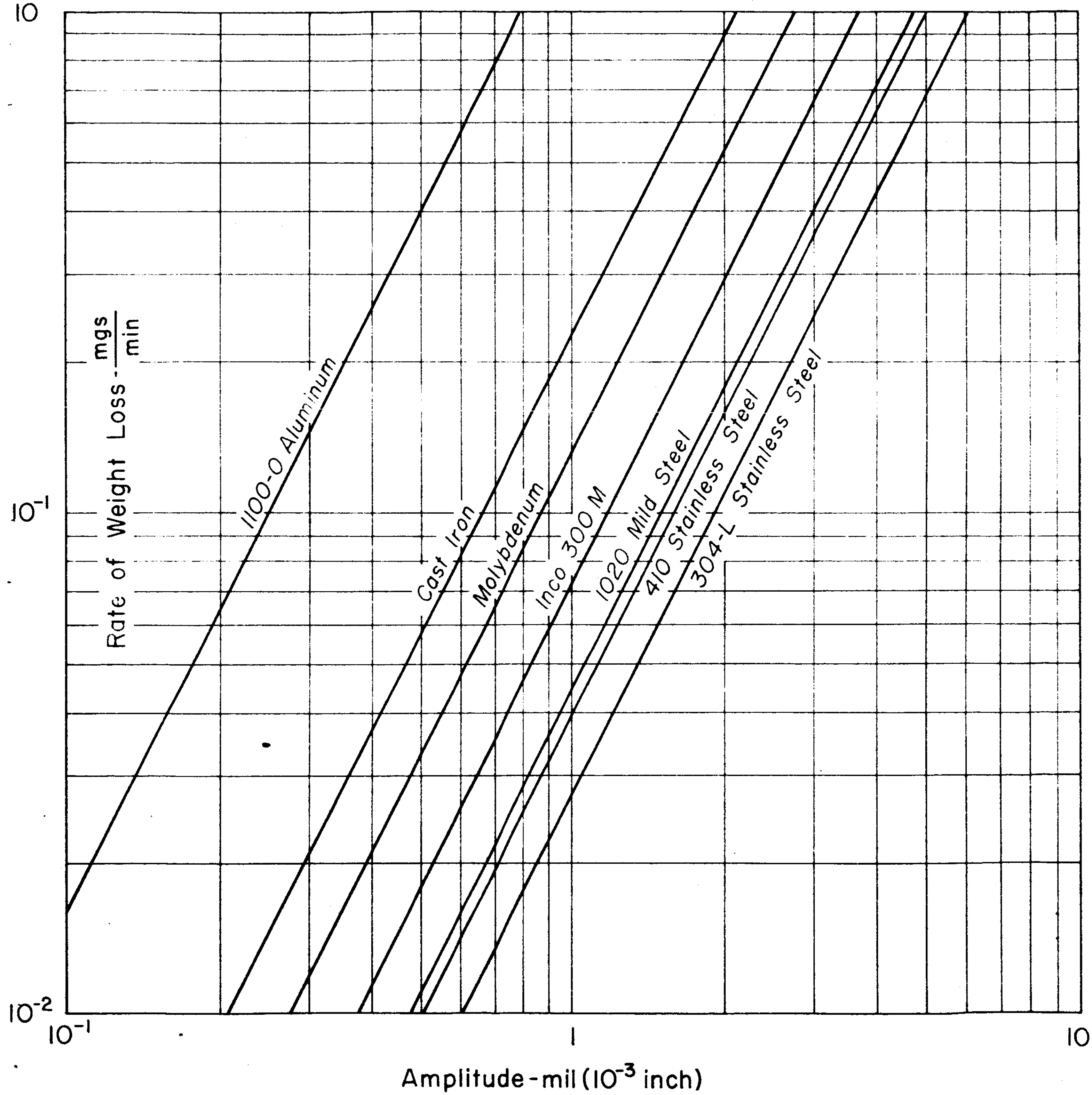


Figure 11-Rate of Weight Loss Vs. Amplitude for Seven Metals; Frequency 15Kcs; Liquid-Tap Water

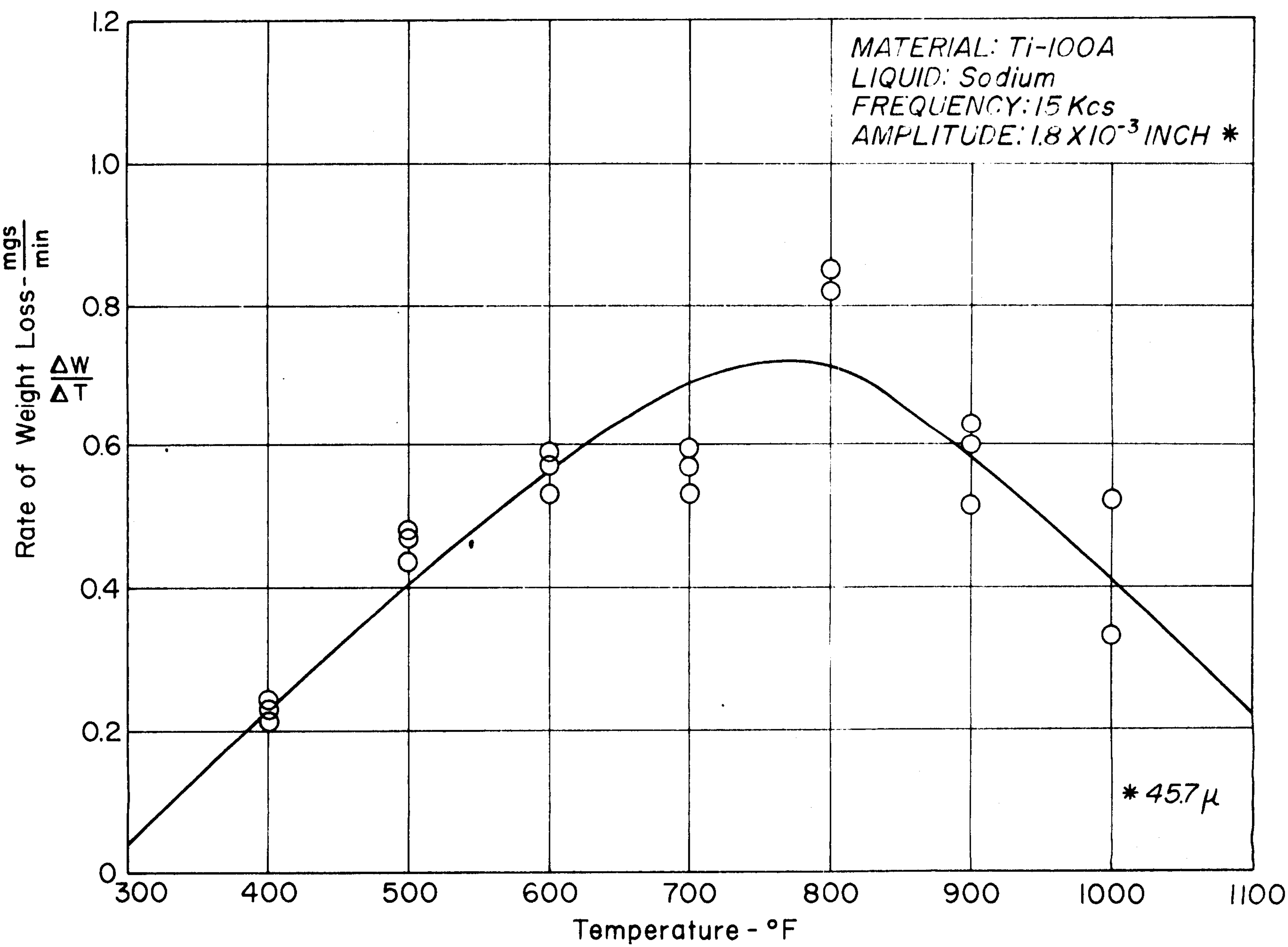


Figure 12-Rate of Weight Loss as a Function of Temperature

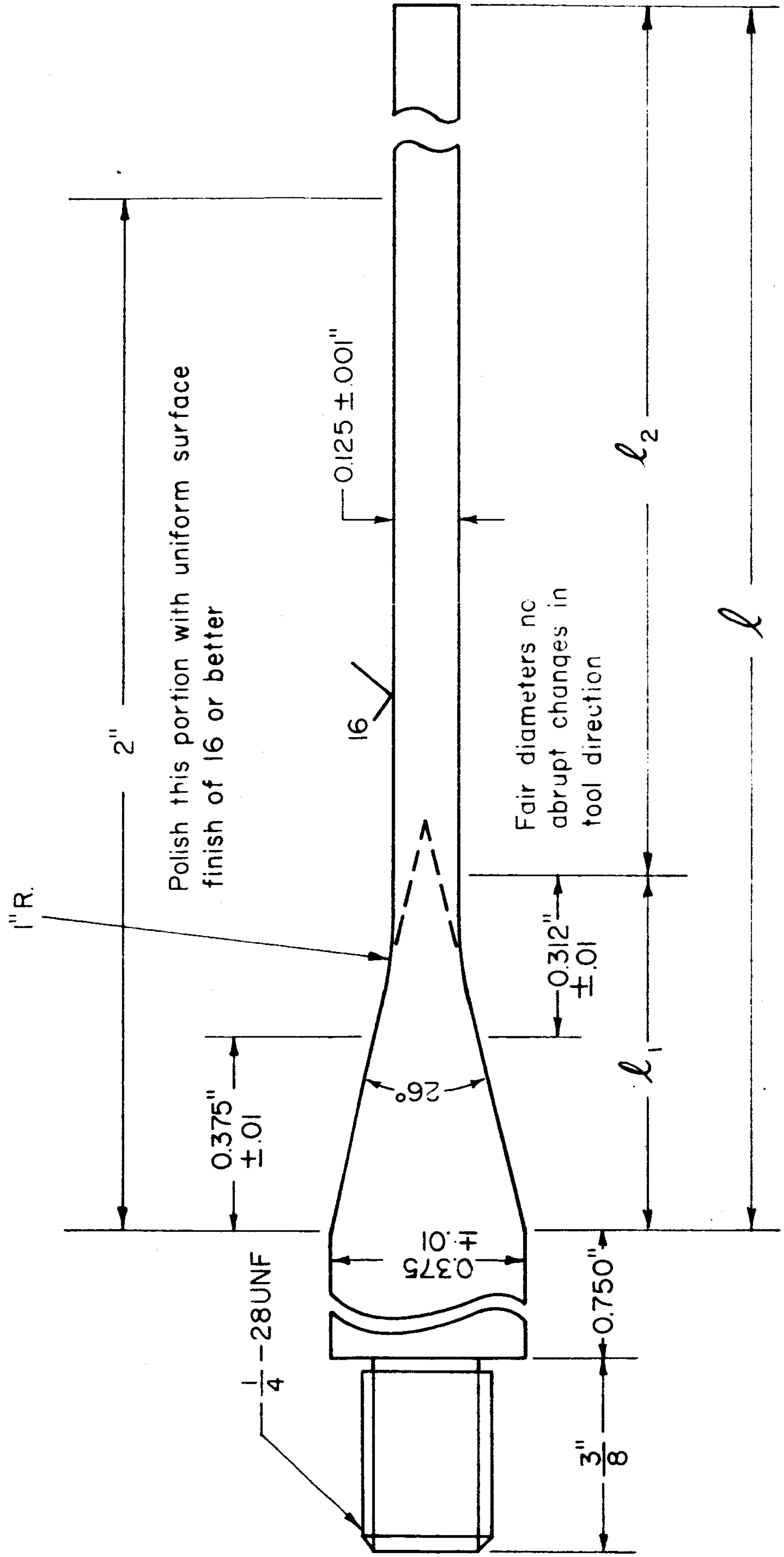


FIGURE 13-HIGH FREQUENCY FATIGUE SPECIMEN

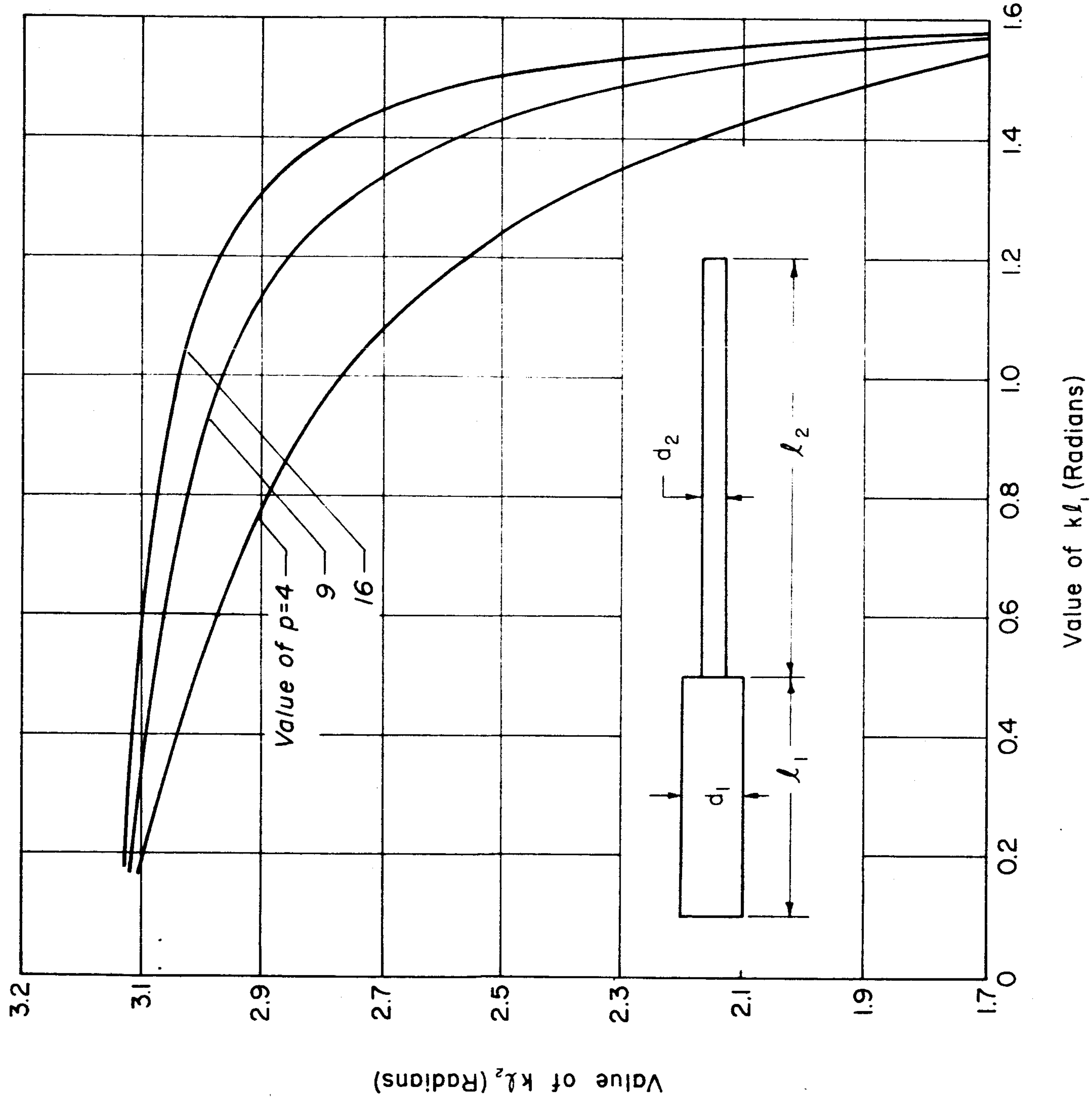


Figure 14-Design Diagram for Fatigue Specimen

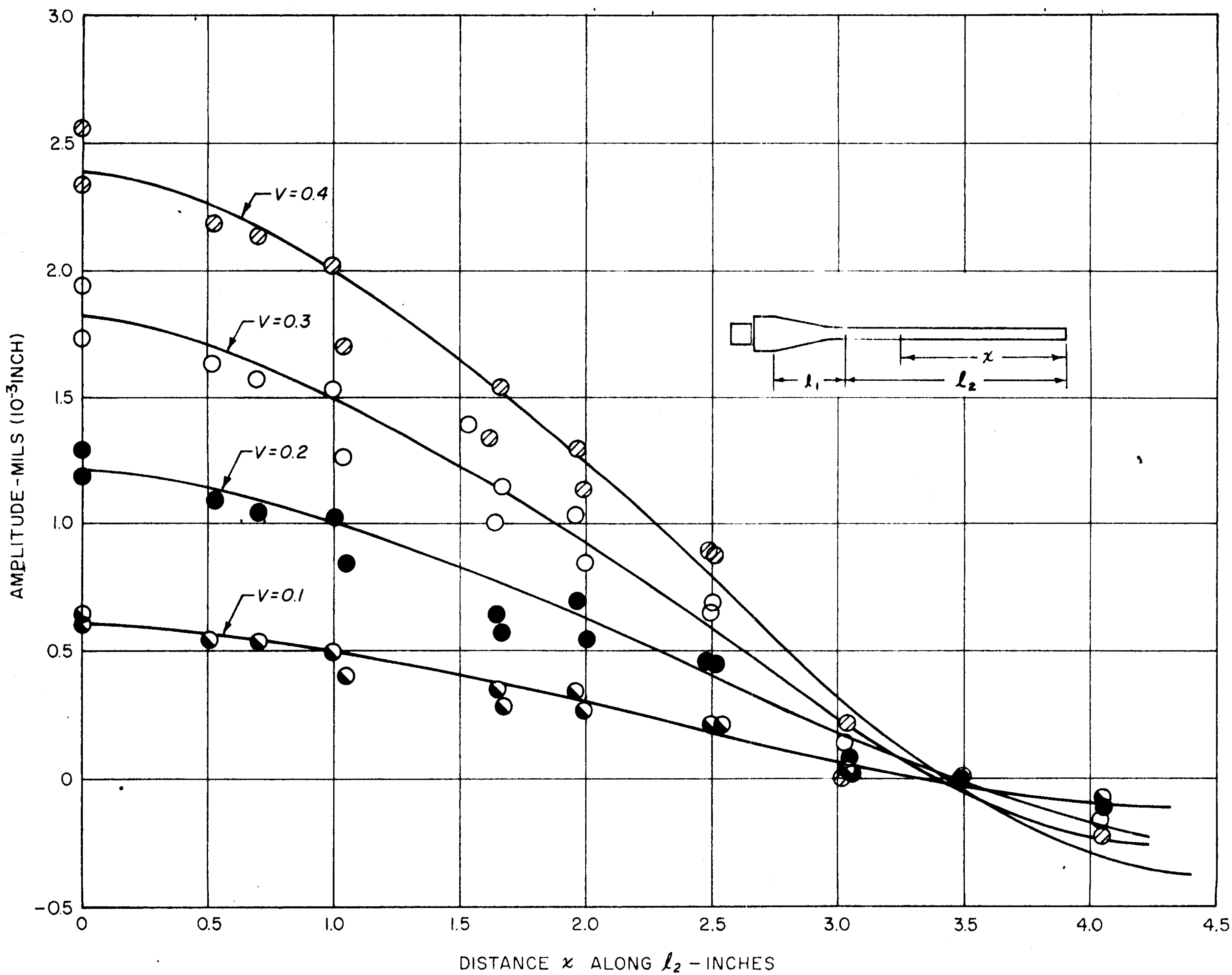


FIGURE 15-CALIBRATION OF FATIGUE SPECIMENS

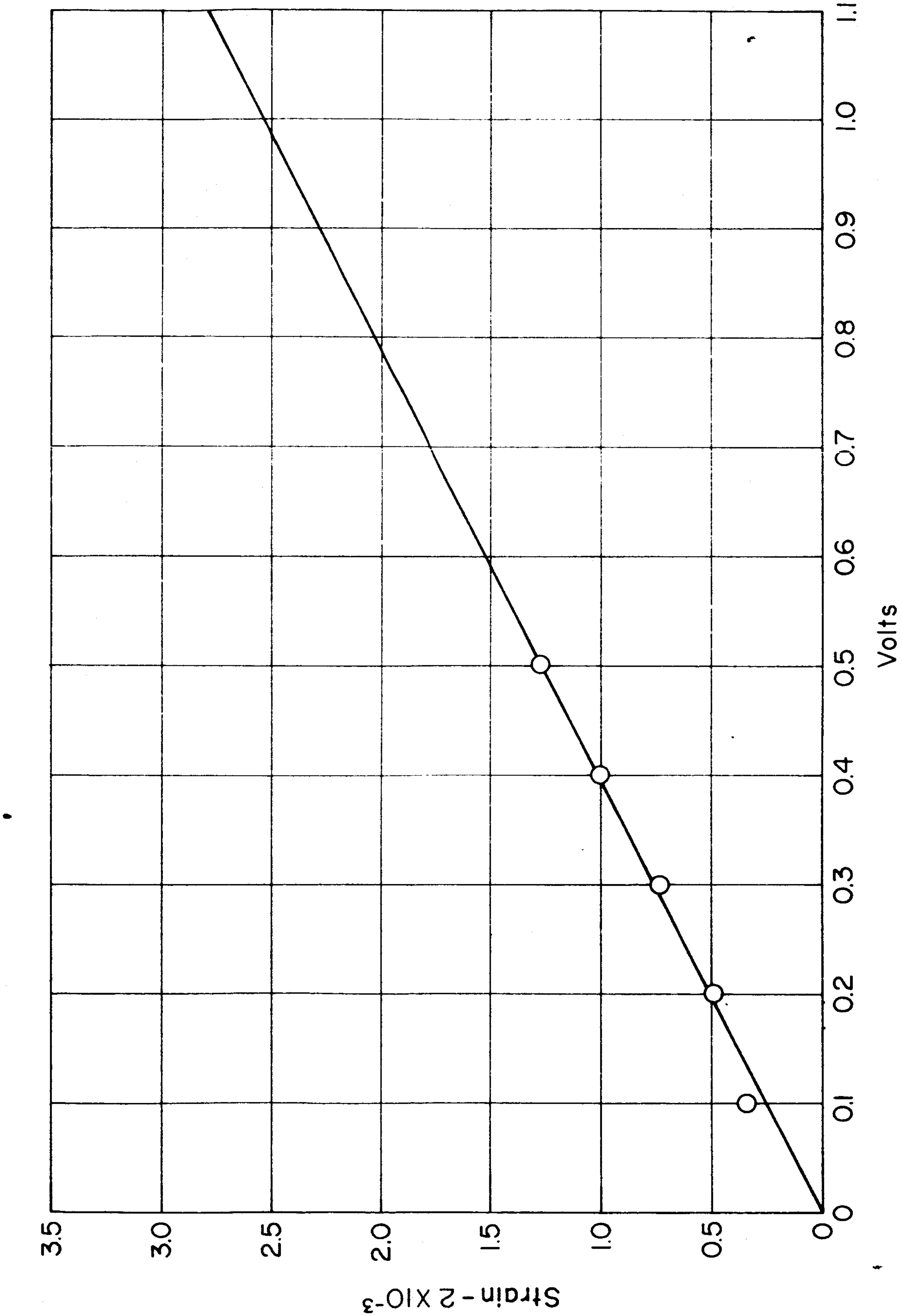


Figure 16-Calibration of Fatigue Specimen

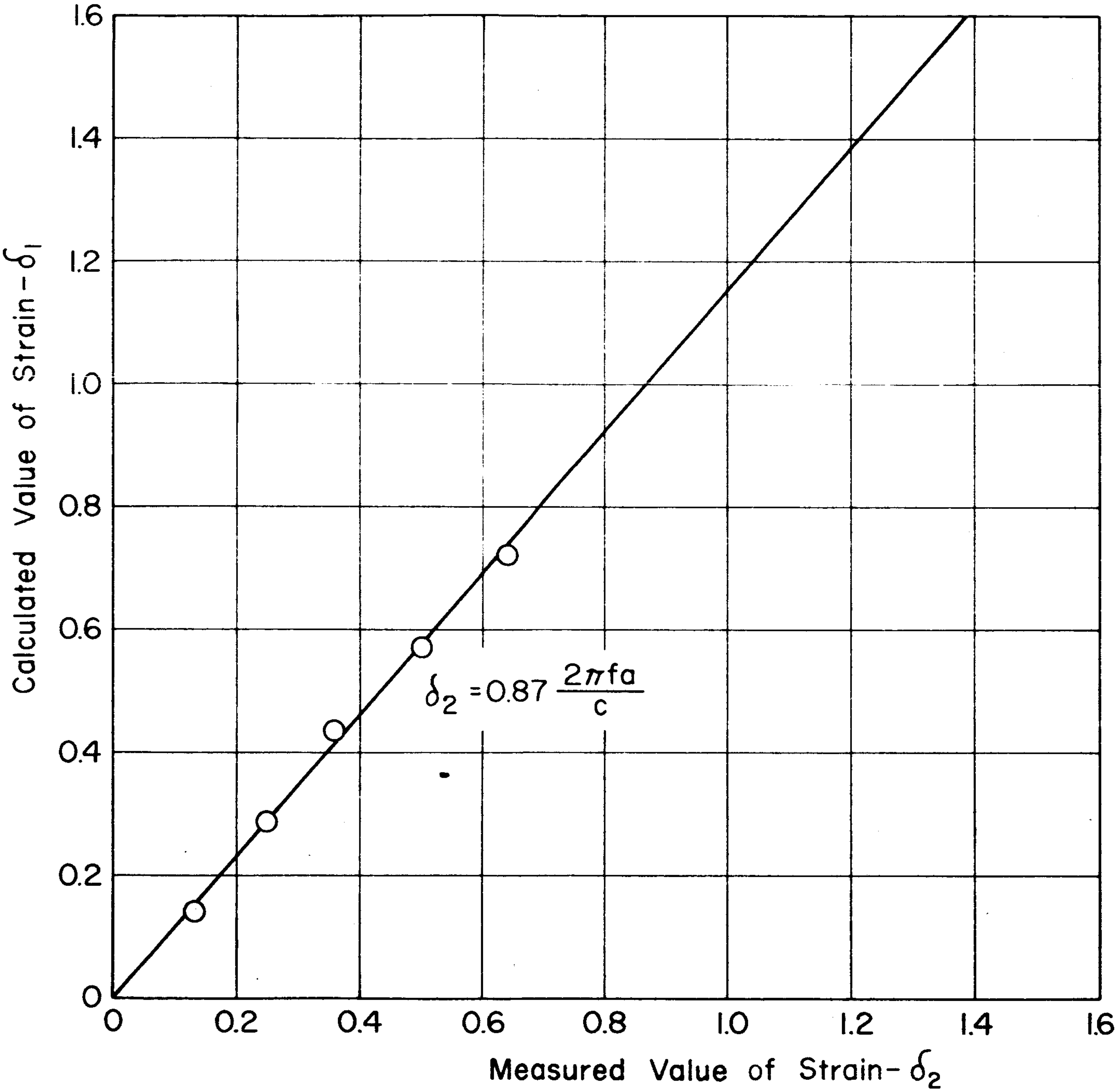


Figure 17-Calibration of High Frequency Fatigue Specimen

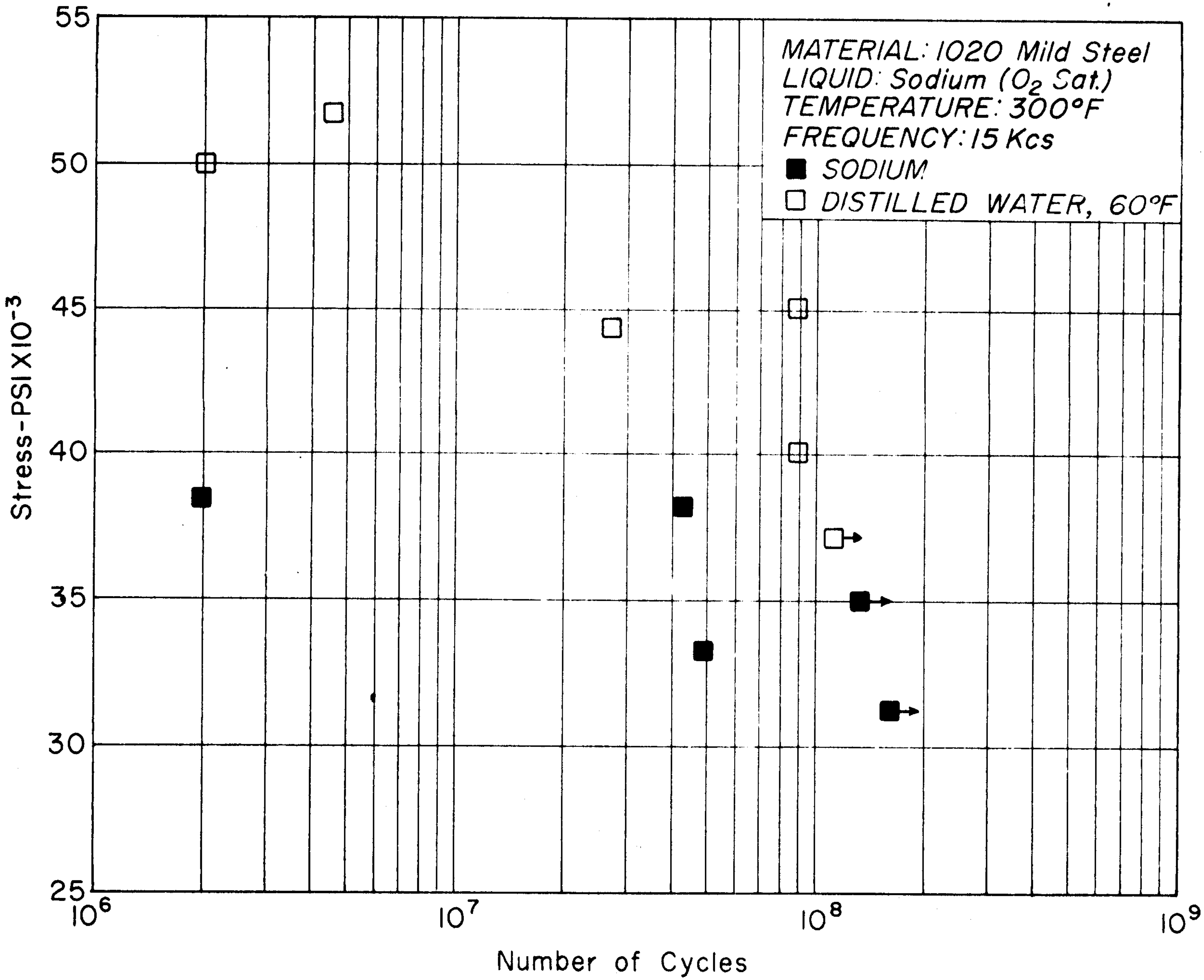
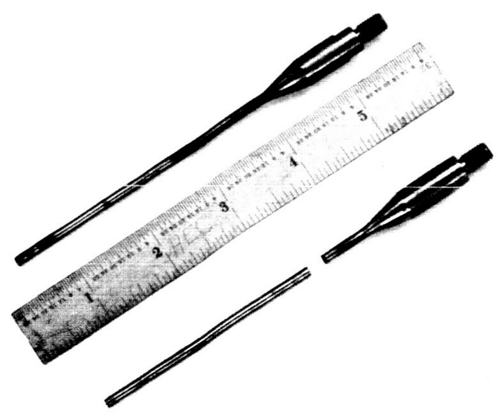


Figure 18-High Frequency Corrosion Fatigue Tests



MATERIAL: 1020 Steel
LIQUID: Sodium, 300°F

TYPICAL FATIGUE SPECIMEN SHOWING FAILURE IN HIGH FREQUENCY TESTS

Figure 19

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